

# THE 2–10 KEV LUMINOSITY AS A STAR FORMATION RATE INDICATOR

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## ABSTRACT

Radio and far infrared luminosities of star forming galaxies follow a tight linear relation. Making use of BeppoSAX and ASCA observations of a well-defined sample of star forming galaxies, we argue that a tight linear relation holds between the 2–10 keV X-ray luminosity and both the radio and far infrared ones. It is suggested that the hard X-ray emission is directly related to the Star Formation Rate. Preliminary results obtained from deep *Chandra* and radio observations of the Hubble Deep Field North show that a similar relation might hold also at high ( $0.2 \lesssim z \lesssim 1.2$ ) redshift.

Key words: X-rays: galaxies – radio continuum: galaxies – infrared: galaxies – missions: BeppoSAX, ASCA, *Chandra*

## 1. INTRODUCTION

Radio continuum and far infrared (FIR) luminosities of star forming galaxies are known to show a *tight linear* relationship spanning four orders of magnitude in luminosity (van der Kruit 1973; De Jong et al. 1985; Condon 1992). This is interpreted as due to the presence of massive, young stars embedded in dust: a fraction of their UV radiation is absorbed by dust grains and reradiated in the infrared band, while supernova explosions may accelerate the electrons producing the observed synchrotron emission (Harwit & Pacini 1975; Helou et al. 1985). Since massive ( $M \gtrsim 5 M_\odot$ ) stars are short-lived, these luminosities are assumed to be indicators of the global Star Formation Rate (SFR) in a galaxy. Following Condon (1992) and Kennicutt (1998), the relation between SFR and radio/FIR luminosities can be written as:

$$\text{SFR} = \frac{L_{1.4\text{GHz}}}{4.0 \cdot 10^{28}} M_\odot/\text{yr} \quad (1)$$

$$\text{SFR} = \frac{L_{\text{FIR}}}{2.2 \cdot 10^{43}} M_\odot/\text{yr} \quad (2)$$

with the FIR flux defined after Helou et al. (1985) as:

$$\text{FIR} = 1.26 \cdot 10^{-11} (2.58 S_{60\mu} + S_{100\mu}) \text{ erg s}^{-1} \text{ cm}^{-2} \quad (3)$$

where  $L_{1.4\text{GHz}}$  is in  $\text{erg s}^{-1} \text{ Hz}^{-1}$ ,  $L_{\text{FIR}}$  in  $\text{erg}^{-1}$  and infrared fluxes in Jy.

Star forming galaxies are known to show luminous soft X-ray emission, originated in hot plasmas associated

to star forming regions and galactic winds. A non linear ( $L_X \propto L_{\text{FIR}}^{0.6}$ ) and much scattered (dispersion of about 2 dex) relation was found between FIR and soft (0.5–3.0 keV) X-ray luminosities measured by the *Einstein* satellite (Griffiths & Padovani 1990).

BeppoSAX and ASCA observations of a sizable sample of star forming galaxies make possible to extend the study of these relations into the hard (2–10 keV) X-ray band.

## 2. THE LOCAL SAMPLE

The atlas of optical nuclear spectra by Ho et al. (1997) (hereafter HFS97) represents a complete spectroscopic survey of galaxies in the Revised Shapley-Ames Catalog of Bright Galaxies by Sandage & Tammann (1981) (RSA) with declination  $\delta > 0^\circ$  and magnitude  $B_T < 12.5$ . Optical spectra are classified in HFS97 on the basis of line intensity ratios according to Veilleux & Osterbrock (1987); galaxies with nuclear line ratios typical of star forming systems are labeled as “H II nuclei”.

We cross-correlated the HFS97 sample with the IRAS Faint Source Catalogue (Moshir et al. 1989, FSC; notice that the FSC only covers the sky with galactic latitude  $|b| > 10^\circ$  and is complete down to limiting fluxes of 0.2 Jy at  $60\mu$  and 1.0 Jy at  $100\mu$ ) obtaining a complete homogeneous sample of 193 nearby ( $z < 0.01$ ) star forming galaxies (hereafter the “parent sample”) which was then cross-correlated with the BeppoSAX and ASCA archives. Eighteen galaxies were detected in the 2–10 keV band with the MECS or GIS instruments. Four additional objects in the field of view of ASCA observations were not detected. The 2–10 keV flux upper limits are too loose to add any significant information, and thus we did not include them in the sample. Radio (1.4 GHz) fluxes were obtained from the Condon et al. (1990, 1996) catalogues.

Most of the data have already been published; in a few cases where published data were not available, we reduced the ASCA archival data. Images and spectra were extracted from the pipeline-screened event files. The images were checked against optical (Digital Sky Survey) and, where available, radio (20 cm) images in order to look for possible source confusions. Fluxes were calculated in the 0.5–2.0 and 2–10 keV bands from best-fit spectra and corrected for Galactic absorption only. One object (M33) was not included in the sample since its broad-band (0.5–10 keV) X-ray nuclear spectrum is dominated by a strong

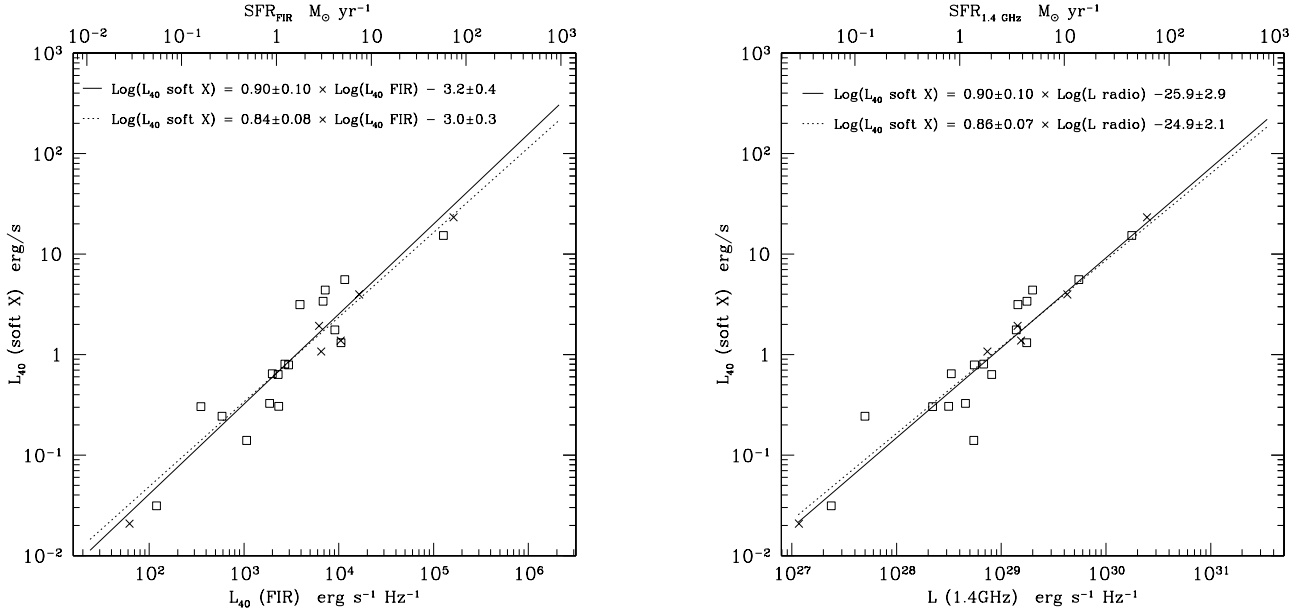


Figure 1. The 0.5–2.0 keV luminosity of local star forming is related to radio and FIR ones. Straight line: best-fit relation for the local sample. Dotted line: best-fit for the local+supplementary samples. Squares: local sample. Crosses: supplementary sample.

variable source (M33 X-8) identified as a black hole candidate (Parmar et al. 2001). Although M33 is identified by HFS97 as an H II nucleus, it has a very low SFR ( $\sim 0.009 M_{\odot}/\text{yr}$ ) so that the spectral signatures related to star formation can be easily hidden by a single powerful source.

Our sample (“local sample”) consists of the 17 galaxies listed in Tab. 1. It contains 11 galaxies with  $\text{SFR} > 1 M_{\odot}/\text{yr}$  out of 77 in the parent sample (14%), and 5 out of 27 with  $\text{SFR} > 3 M_{\odot}/\text{yr}$  (19%). Since the parent sample is complete within the statistical errors, these numbers represent an estimate of our sample completeness. All statistical tests presented here are performed on this sample unless otherwise stated.

In the figures we also plot data for 6 other well-known starburst galaxies which were not in the HFS97 survey because they are in the southern hemisphere. On the basis of their line intensity ratios they should be classified as H II nuclei. In Tab. 1 we label them as “supplementary sample”.

### 3. X-RAYS AND THE STAR FORMATION RATE

As a preliminary test, we perform a least-squares analysis for the well-known radio/FIR correlation, which yields

$$\text{Log}(L_{\text{FIR}}) = (0.94 \pm 0.09) \text{Log}(L_{1.4}) + 16.4 \pm 2.5 \quad (4)$$

The dispersion around the best-fit relation is estimated as:

$$\delta = 1/N \cdot \sum |(L_{\text{obs}} - L_{\text{pred}})/L_{\text{pred}}| \quad (5)$$

where  $L_{\text{pred}}$  is the luminosity expected from the best fit relation and  $L_{\text{obs}}$  the observed one. For the radio/FIR correlation (eq. 4) one has  $\delta \simeq 43\%$ .

Following Helou et al. (1985) we also calculate the mean ratio  $q$  between the logarithms of FIR and radio fluxes, obtaining  $q \simeq 2.05$  with a variance  $\sigma \simeq 0.23$ . These values can be compared with the mean  $q = 2.34 \pm 0.01$  for the 2809 galaxies in the IRAS 2 Jy sample by Yun et al. (2001). Although our sample shows a lower  $q$ , this result may not be statistically significant.

As a further test we checked the soft X-ray/FIR relation (Fig. 1), finding

$$\text{Log}(L_{.5-2}) = (0.90 \pm 0.10) \text{Log}(L_{\text{FIR}}) - 3.2 \pm 0.4 \quad (6)$$

$$\text{Log}(L_{.5-2}) = (0.90 \pm 0.10) \text{Log}(L_{1.4}) + 14.1 \pm 2.9 \quad (7)$$

with mean  $\delta$ 's of 58% and 46%, respectively.

Our result is consistent with the  $L_{0.5-4.5\text{keV}} \propto L_{\text{FIR}}^{0.95 \pm 0.06}$  relation found by David et al. (1992) for normal and star-

Table 1. Galaxies in the local sample. All galaxies were observed by ASCA, except those marked with \* observed by BeppoSAX.

LOCAL SAMPLE		
M82*	NGC 2276	NGC 4449
M101	NGC 2403	NGC 4631
M108	NGC 2903	NGC 4654
NGG 891	NGC 3310	NGC 6946
NGC 1569	NGC 3367	IC 342
NGC 2146	NGC 3690	
SUPPLEMENTARY SAMPLE		
NGC 55	NGC 1672	NGC 3256
NGC 253*	NGC 1808	Antennae

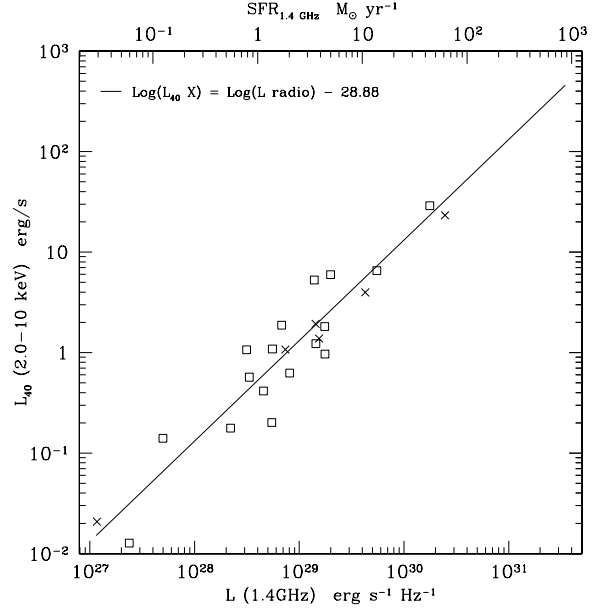
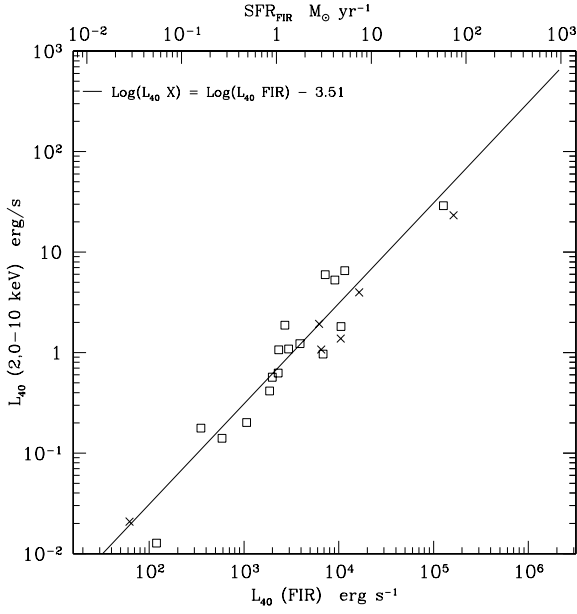


Figure 2. The 2–10 keV luminosity of local star forming galaxies is linearly related to radio and FIR ones. Symbols as in fig. (1).

burst galaxies from the IRAS Bright Galaxy Sample, but is inconsistent with the much flatter relationship obtained by Griffiths & Padovani (1990) for a sample of IRAS selected galaxies ( $L_{0.5-3\text{keV}} \propto L_{60\mu}^{0.62 \pm 0.14}$ ) and for a sample of starburst/interacting galaxies ( $L_{0.5-3\text{keV}} \propto L_{60\mu}^{0.70 \pm 0.12}$ ).

The inclusion of the supplementary objects (Tab. 1) in our analysis would lead to a slight flattening of the slope, i.e.  $L_{0.5-2.0\text{keV}} \propto L_{\text{FIR}}^{0.84 \pm 0.08}$ ; likewise, if we use the  $60\mu$  luminosity instead of FIR, we obtain  $L_{0.5-2.0\text{keV}} \propto L_{60\mu}^{0.83 \pm 0.10}$  with  $\delta = 64\%$ . However these results are still consistent with slopes derived in eq. (6) and (7) within  $1\sigma$ .

On the other hand the radio/FIR/hard X-ray relation is definitively linear. In Fig. (2) we plot 2–10 keV luminosities versus FIR and radio ones. Least-squares fits yield:

$$\text{Log}(L_{2-10}) = (1.08 \pm 0.09) \text{Log}(L_{\text{FIR}}) - 3.8 \pm 0.3 \quad (8)$$

$$\text{Log}(L_{2-10}) = (1.04 \pm 0.11) \text{Log}(L_{1.4}) + 10.1 \pm 3.4 \quad (9)$$

with mean  $\delta$ 's of 51% and 69%, respectively. The linearity and the dispersion are not significantly changed neither by the inclusion of the supplementary sample ( $L_{2-10} \propto L_{\text{FIR}}^{0.98 \pm 0.07}$  and  $L_{2-10} \propto L_{1.4}^{0.98 \pm 0.07}$ ,  $\delta = 50\%$  and  $57\%$  respectively), nor by the use of the  $60\mu$  luminosity ( $L_{2-10} \propto L_{60\mu}^{1.00 \pm 0.11}$ ).

It is also worth noticing that while the soft X-ray relations involve some further uncertainties related to the possible presence of intrinsic absorption, this is negligible in the 2–10 keV band for column densities usually found in normal galaxies. A high column density ( $N_{\text{H}} \gtrsim 10^{22}$ ) could partially obscure a possible AGN contribution; how-

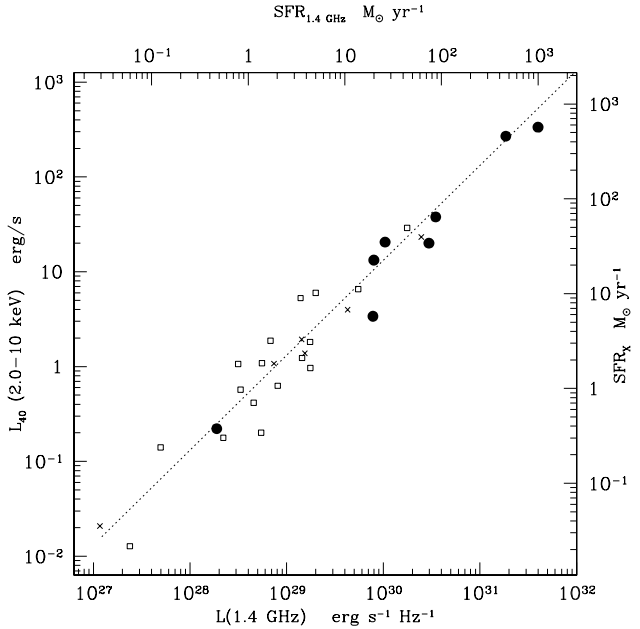


Figure 3. The radio/X-ray luminosity relation holds in the Hubble Deep Field too. Open symbols as in fig. (1). Filled circles: deep sample. Line: best fit for local galaxies (eq. 11). The two galaxies with highest luminosity are both at  $z \simeq 1.2$

ever this seems unlikely for our sample because of the selection of the objects by optical spectroscopy and of their moderate X-ray luminosity ( $< 10^{42}$  erg/s).

The existence of a tight linear relation implies that the three considered bands all carry the same information.

Since the radio and far infrared luminosity are indicators of the SFR, the 2–10 keV luminosity should also be an indicator of SFR.

By repeating the best fit procedure under the assumption of strict linear relationships, consistent within  $1\sigma$  with the result of eq. (8) and (9), we find:

$$\text{Log}(L_{2-10}) = \text{Log}(L_{\text{FIR}}) - 3.51 \quad (10)$$

$$\text{Log}(L_{2-10}) = \text{Log}(L_{1.4}) + 11.12 \quad (11)$$

From eq. (1) and (2) we propose:

$$\text{SFR} = 1.7 \cdot 10^{-40} L_{2-10\text{keV}} \quad \text{M}\odot/\text{yr} \quad (12)$$

with  $L_{2-10 \text{ keV}}$  in erg/s.

#### 4. STAR-FORMING GALAXIES IN THE HUBBLE DEEP FIELD

The 1 Ms *Chandra* (Brandt et al. 2001) and the radio 8.4 GHz (Richards et al. 1998) catalogs of the Hubble Deep Field North (HDF) reach a limiting flux which is sufficiently deep to detect star-forming galaxies at redshifts up to  $z \sim 1.2$ , and can be used to check whether the radio/X-ray relation holds also for distant galaxies.

Radio and X-ray positions were matched with an encircling radius of  $1.1''$ . All objects classified by Richards et al. (1998) as AGN, or with an elliptical or undefined morphology were excluded; all other objects are accepted as “candidate starbursts”. Fluxes at 1.4 GHz were calculated making use of 8.4 GHz data and spectral indexes measured for each object and reported in Richards et al. (1998). Redshifts were taken from Cohen et al. (2000). Fluxes in the 2–10 keV were derived from a power-law fit to the observed 0.5–8 keV counts by Brandt et al. (2001). Radio and X-ray k-corrections were calculated for a range of spectral indexes and redshifts; we chose to use mean k-corrections since the induced error would not significantly affect the rest-frame fluxes.

We find that radio and X-ray luminosities of candidate starburst galaxies at larger redshifts follow the same relation we observe in the very local universe (Fig. 3), which now spans 5 orders of magnitude.

#### 5. CONCLUSIONS

We have analyzed a small but well defined sample of 17 star forming galaxies for which there is a homogeneous information on optical, FIR, radio and X-ray bands (local sample). The BeppoSAX and ASCA X-ray data have been corrected for Galactic absorption only. In agreement with a previous work (David et al. 1992) we find that the logarithms of the soft (0.5–2 keV) X-ray luminosities are linearly correlated with the logarithms of either radio (1.4 GHz) and FIR luminosities, and that within the statistical errors these relationships are consistent with linearity between the corresponding luminosities. We have extended our analysis to the harder X-ray band, essentially free from internal absorption which may affect the soft X-ray fluxes,

and found that there is a tight linear correlation between the X-ray luminosities in the 2–10 keV interval with both the radio and the FIR luminosities, normally assumed as the indicators of the star formation rate. We conclude that the origin of the hard X-ray emission must be closely related to star formation.

By selecting candidate starburst galaxies from the HDF North, whose redshift range extends up to  $z \sim 1.2$ , we find that their X-ray ( $L_{2-10}$ ) and radio ( $L_{1.4}$ ) luminosities closely follow the same linear relationship derived for the local sample. This linear correlation encompasses five orders of magnitude in luminosity, up to  $L_{2-10} \sim$  several  $10^{42}$  erg s $^{-1}$  and a corresponding star formation rate  $\sim 1000 \text{ M}\odot \text{ yr}^{-1}$ . We also notice that for the highest luminosity galaxies (which have  $z \simeq 1.2$ ) the observed 2–10 keV band corresponds to a rest-frame 4.5–22 keV, where the emission is likely to be non-thermal. A plasma hot enough to dominate the emission in this band would pose many problems in heating and bounding the gas.

The way to understand the physics involved in hard X-ray emission must go through a careful analysis of *Chandra* and XMM-*Newton* observation, which have the necessary spatial resolution and spectral sensitivity. Moreover, since the radio/FIR relation holds also locally in galaxies down to scales of about 100 pc, it is worth remarking that the two star-bursting nuclei of NGC 3256 closely follow the hard X-ray/radio relation, as suggested by our preliminary work on the *Chandra* observation for this galaxy. The explanation of the radio/FIR correlation is still a matter of discussion; we hope that these results may help in clarifying this issue. We are currently analysing possibilities for a theoretical interpretation which, along with further constraints on this observational results, will be the subject of a forthcoming paper.

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